3-D SELF-ASSEMBLED SOI MEMS: FABRICATION AND NUMERICAL SIMULATION

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ABSTRACT

The advantages of thin film SOI (Silicon-on-Insulator) technology for MOS circuits compared with thick SOI and bulk silicon MOS techniques are nowadays well known. Among them, we can mention a lower power consumption, better performance on high frequency operation and resistance to irradiation as well as better high temperature characteristics. These advantages in addition to a direct MEMS-IC integration make thin film SOI an attractive process for the manufacture of high quality MEMS and MOS integrated circuits for space applications.

In this work, we present tridimensional (3-D) self-assembled multilayered SOI MEMS structures that can be used (but not limited) as flow sensors, thermal actuators and high frequency inductors. These MEMS consist of layers of Si, Si_3N_4 and Al deposited at different temperatures, and the final shape of the structure can be very different depending on the number, the nature and the thickness of the layers that are deposited. If the system consists only of one layer of Si, the structure remains flat after the release, whereas in the bilayer case (Si and Si_3N_4) the structure bends up. This is due to the thermal expansion coefficient of the Si_3N_4, which is higher than the Si one, and therefore the upper part of the structure contracts more than the lower part resulting in a curved shape. The thermal expansion coefficient of the Al being even greater than the Si_3N_4 one, we would then expect a larger curvature of the structure in the trilayer case, but considering the Al deposition temperature and the geometry we can demonstrate that the shape is rather flat. To obtain a curly shape in the trilayer structure an additional thermal step is needed. It could be a two minutes RTA (Rapid Thermal Annealing) at 600°C or a lower temperature annealing (432°C) but for a longer time (30 min). In order to make quantitative comparisons with numerical simulations, the final shape of these structures was completely characterized using laser interferometry.

Numerical simulations were made using the finite element code Oofelie. This code allows us to simulate the fabrication process in a realistic way adding layers one by one and considering the residual stress of the layers already deposited. In this way, an analysis of intermediate stresses in the different layers can be done, and if it is the case, additional residual stresses that do not have a thermal origin can be included. In order to model accurately the 3-D MEMS final shape, which is characterized by large displacements, the code takes into account the geometric nonlinearity. Numerical simulations are in good agreement with experimental data and with available analytical results. Reliable numerical simulations are very helpful to accelerate the MEMS design phase when complex geometries are involved.

1 - INTRODUCTION

Concerning power consumption, high frequency response, high temperature operation and resistance to radiation, integrated circuits made with thin film SOI (Silicon-on-Insulator) technology have better properties than bulk silicon MOS techniques [1]. These characteristics make thin SOI a very attractive technology for using it in the harsh conditions of space applications. Not only integrated circuit but also the fabrication of MEMS with this technique is very interesting because besides the good characteristics mentioned above a real integration between MEMS and electronic components is almost immediate.

Most of the products available on the market and nearly all of the published results in the literature concern planar MEMS devices, it means microstructures characterized by displacements in the wafer plane or out-of-plane movements (vertical) of small magnitude. In this work we show 3-D SOI MEMS that can be used as flow sensors, thermal actuators and high frequency inductors (Fig. 1). These MEMS consist of layers of Si, Si_3N_4 and Al, deposited at different temperatures. The assembly of these 3-D structures is obtained through the control of residual stresses originated by the mismatch between the thermal expansion coefficients of the different layers. For a better control of the final shape, an additional thermal treatment may be necessary.

As in any design process, simulations before the fabrication shorten a lot the development cycle. The simulation of MEMS is a challenging task due to the strong coupling between several physical effects like thermal, electrical and mechanical. We show here how these MEMS can be simulated using the multiphysics finite element code, called Oofelie [2].

The details of the fabrication process are given in Section 2 and in Section 3 we describe the MEMS behavior when the number of layers is changed and additional thermal processes are made. Section 4 shows some numerical results and a procedure for optimizing the final shape of the MEMS is introduced in Section 5. Future work and conclusions are given in Section 6.

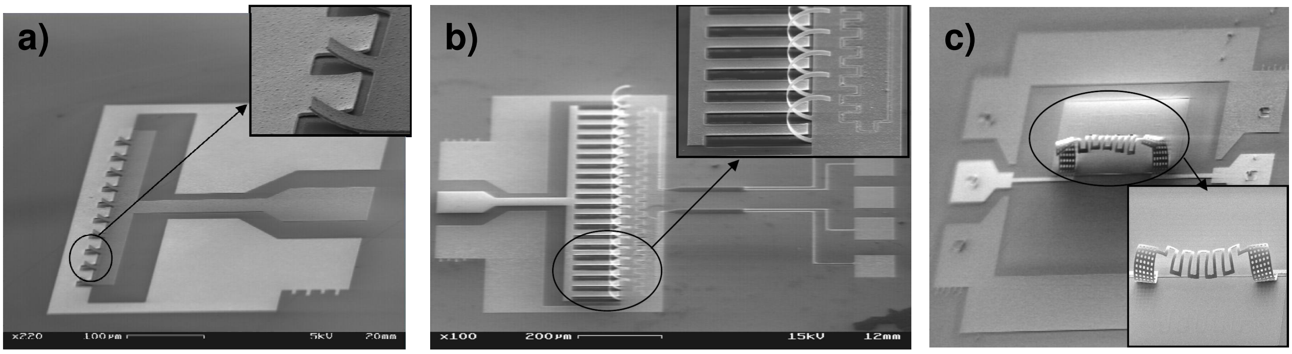

Figure 1: 3-D self-assembled MEMS: a) flow sensor, b) thermal actuator, c) inductor.

2 - FABRICATION

The fabrication process [3] is sketched in Fig. 2. Over a SOI wafer, a Si_3N_4 layer is deposited at 800°C using LPCVD (Low Pressure Chemical Vapor Deposition). Following, Al is evaporated over the Si_3N_4 layer at a lower temperature (150°C). After that, a photolithographic step is made in order to etch with plasma (dry etching) the Si, Si_3N_4 and Al layers. The release of the structure is finally made by etching the oxide with a mixture of HF and isopropanol (wet etching). Caution has to be taken in this step to avoid the release of fixed parts; therefore, an adequate design of the structure and a careful control of the wet etching time are required. For the self-assembling of the trilayer structure, an additional thermal process is needed. One possibility is a rapid thermal annealing at 600°C for 2 minutes, but good results can also be obtained with a thermal annealing at a lower temperature (432°C) for a longer time (30 min). In this last alternative, because the annealing temperature is quite lower than the Al fusion temperature, no change of mechanical and electrical properties is observed.

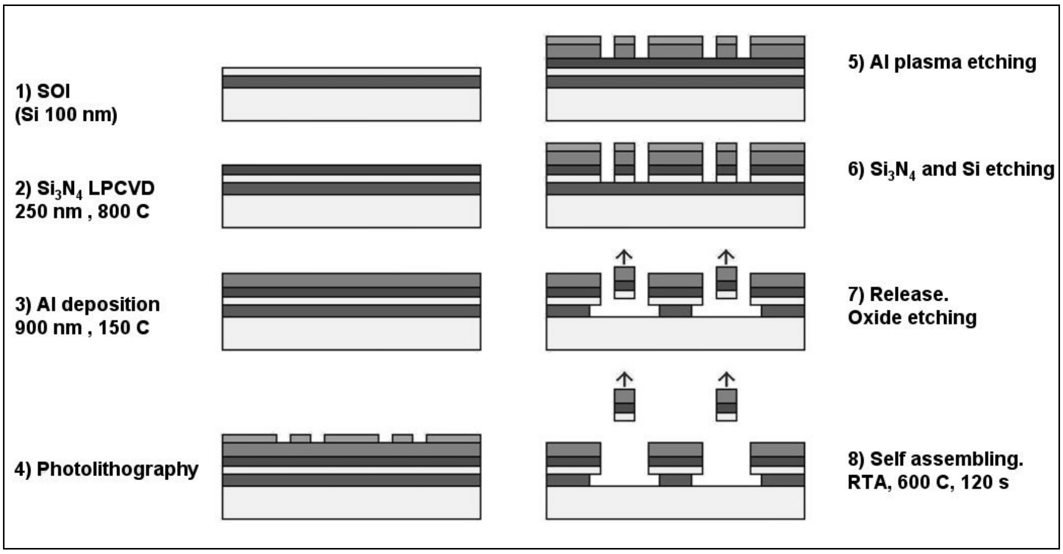

Figure 2: Fabrication process of multilayered beams.

3 - MECHANICAL BEHAVIOR

Most of the time residual stress is an issue to avoid in integrated circuits and MEMS, but in the devices that we are presenting, it is not the avoiding but the control of the residual stress which allows the self-assembling of the structure. The origin of the stress is the mismatch between the thermal expansion coefficients of the materials and in order to better understand the consequences of the thermal stress, several tests have been made. It is observed experimentally that the shape of the final structure can be very different depending on the number of layers that is deposited. If the system consists only of one layer of Si, the structure remains flat after the release (Fig. 3a) as it is expected. While in the bilayer case (Si and Si_3N_4) the structure bends up (Fig. 3b). This is because the thermal expansion coefficient of the Si_3N_4 is greater than the Si coefficient, and therefore as the upper part of the structure contracts more than the lower part a curved shape is obtained. Considering that Al has the greatest thermal expansion coefficient of the three materials, the trilayer case could be more curved than the bilayer, but there are two factor to taken into account to understand why this is not the case (Fig. 3c). One is that the deposition temperature of the Al is much lower than the Si_3N_4 one; accordingly, the bigger thermal expansion coefficient of the Al is not so effective. The second concerns the geometry. As the Al layer is very thick compare with the other two layers, the Si_3N_4 is now at the lower part of the beam and thus compensates the contraction of the Al, thus leading to a rather flat final shape for the trilayer. To obtain a curly shape in the trilayer system an additional thermal process is necessary. After 2 minutes RTA at 600°C, the achieved shape is shown in Fig. 3d. In this last process, as the temperature is close to the fusion temperature, the Al can melt locally and some mechanical and electrical properties can change. A longer annealing at a lower temperature (30 min at 432°C) avoids these difficulties and the final shape is practically the same.

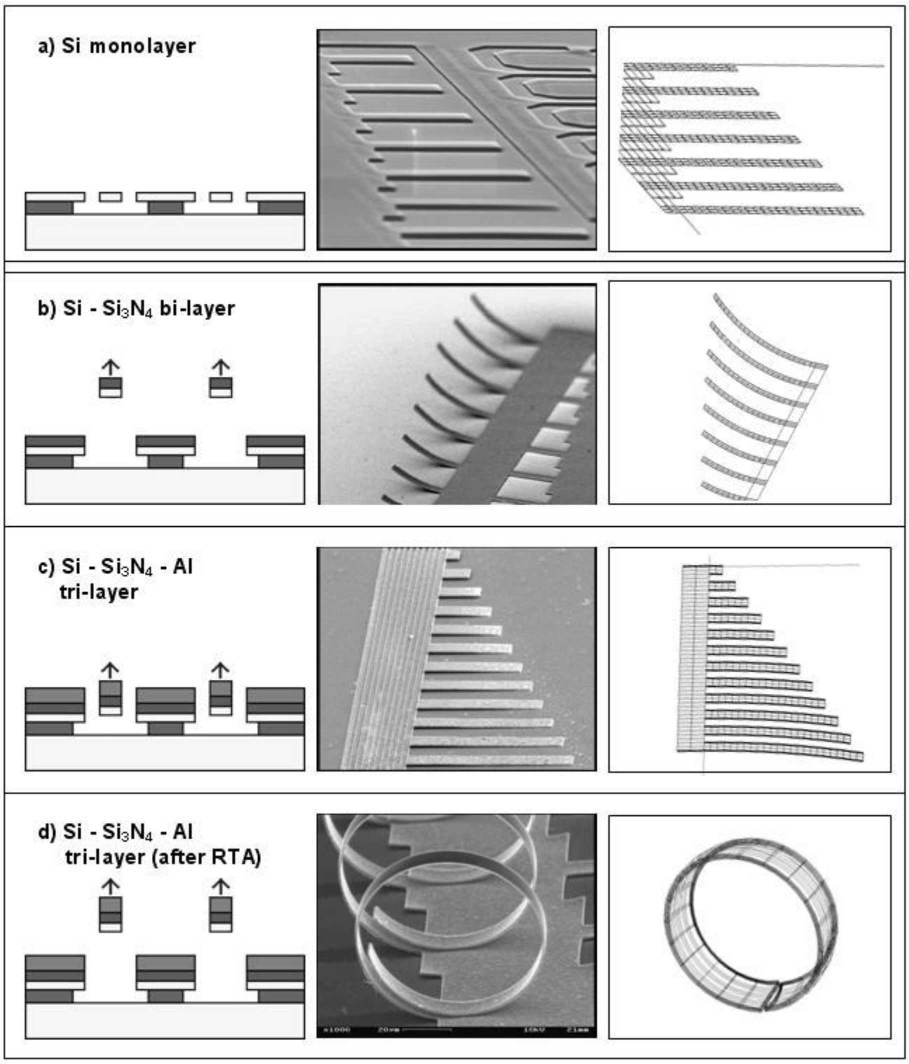

Figure 3: Different behavior of one, two and three layered structures.

4 - NUMERICAL SIMULATION

One of the main characteristics of the 3-D MEMS presented in this work is their large displacements out-of-plane wafer. For small displacements the relationship between strain ε and displacement *u* can be well approximated by a linear equation and in one dimension the expression is

$$\varepsilon = \frac{\partial u}{\partial x} \tag{1}$$

Under linear conditions, it predicts that if the loads are multiplied by a given factor, the displacements are also multiplied by the same factor. When the displacements generated by the loads are small this is a valid hypothesis, but when the displacements are large compared to the dimensions of the microstructure this assumption can give very wrong results. For large displacements the above equation is no longer valid and has to be replace with the following nonlinear expression

$$\varepsilon = \frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial u}{\partial x}\right)^2 \tag{2}$$

The other characteristic of this kind of MEMS is the strong coupling between the thermal and mechanical fields, and because of that, the thermal effect cannot be considered merely as a perturbation. Specifically, from the finite element point of view, for a good simulation of these systems the analysis has to be geometrically nonlinear with a full integrated calculation of the thermal and mechanical fields. Results were obtained using second order elements, and even though the cases studied here are rather simple, simulations were made using tridimensional elements which give us the possibility to model more complex geometries (Fig. 1). The code allows the addition of the layers one by one; therefore, the fabrication process can be simulated in a realistic way and intermediate stresses can be analyzed. This way of simulation also permits the inclusion of stresses without a thermal origin, as for example the stress generated by the lattice mismatch at the interface between layers.

In the right side of Fig. 3 we show how the mechanical behavior can be qualitatively described. For a more quantitative comparison the shape of several bilayered cantilevers have been measured using laser interferometry. In Fig. 4 we can see various profiles of bilayers with lengths from 140 to 220 µm. The fit using a circle is very good and the radius of curvature obtained is practically the same for all the cantilevers. Using the parameters in Table 1, the radius of curvature obtained numerically is R = 47.37 µm. This value is in good agreement with the value calculated with analytical expressions in [4]. The difference with the experimental radius is small, and therefore, we can say that the bending of the bilayered cantilevers is mainly due to thermal effects.

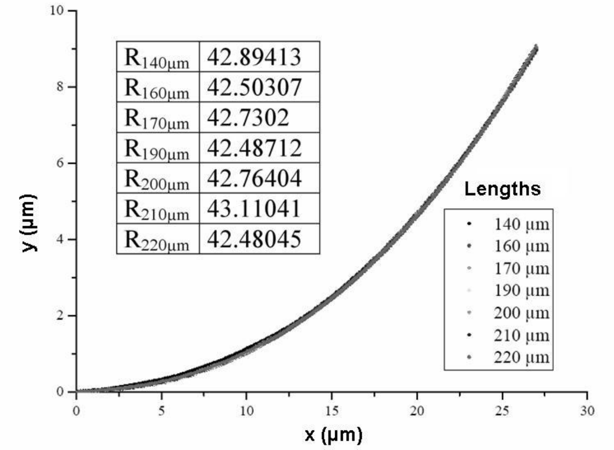

Figure 4: Shapes of bilayered cantilevers of various lengths and fitted radii of curvature.

Table 1: Main characteristics of the bilayers (Si-Si_3N_4) presented in Fig. 4.

	1st layer: Si	**2nd layer: Si_3N_4**
Young's modulus	130 GPa	270.0 GPa
Poisson's ratio	0.279	0.27
Thermal expansion coeff.	2.33E-6	6.06E-6 (1/°C)
Thickness	100 nm	100 nm
Deposition temperature	-	800 °C

In Fig. 5 we show a simulation that demonstrates the operation principle of the thermal actuator shown in Fig. 1b. The maximum deflection occurs a room temperature, and the structure goes down to the wafer surface when the temperature is increased. The increment of temperature is obtained by means of a microheater composed of a thin doped polysilicon layer in which a tunable DC current is flowing (Joule effect) and located at the anchor of the cantilever (Fig. 1b). Thanks to the small size of the fabricated MEMS the thermal response of this microstructures is very small (< 1 ms).

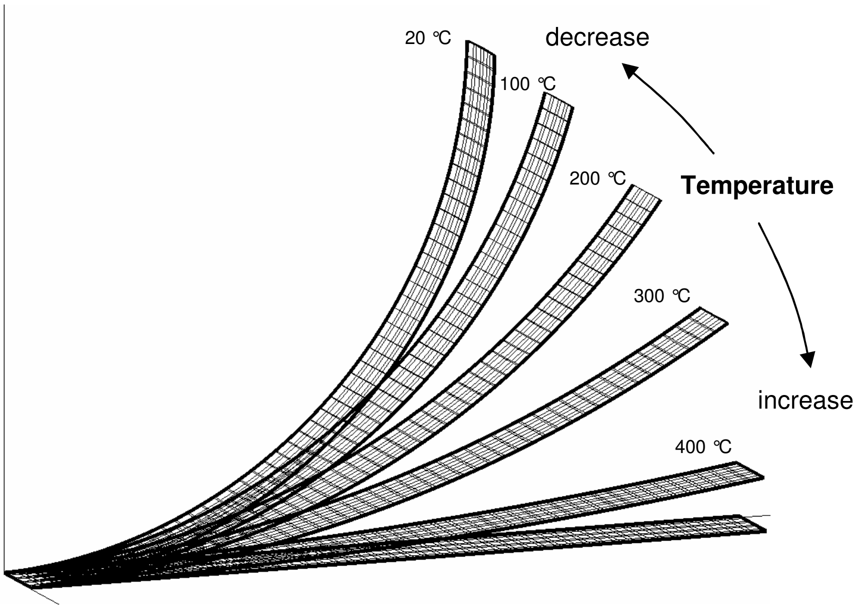

Figure 5: Principle of operation of the thermal actuator showed in Fig. 1b.

In the flow sensor (Fig. 1a) thermal effects take part only in the assembling of the structure. The structure will deform under the pressure applied by the fluid on the 3-D MEMS surface and thus its operation is purely mechanical. The change of shape, and therefore the intensity and direction of the flow, can be monitored by the measurement of capacitance changes between the multilayered cantilever and the substrate or putting a piezoelectric material at the anchor in order to measure changes of stress at that point.

5 - OPTIMIZATION

Besides the description of the fabrication and operation of MEMS, numerical tools (and also analytical expressions when they are available) play an important role in the optimization of the final structure. In Fig. 6, for instance, we show the curvature of a bilayered cantilever, which has a silicon layer of 100 nm, as a function of the thickness of the Si_3N_4 layer. The maximum deflection occurs for a Si_3N_4 thickness of approximately 35 nm, much thinner than the Si layer.

The same analysis can be done for the trilayered cantilever, and in Fig. 7 we show the curvature as a function of the thicknesses of Si_3N_4 and Al. For each parameter, the behavior of the curvature is similar to that in Fig. 6. The point (0,0) where the curvature is null corresponds to a single layer of Si. Because the thermal expansion coefficient of Al is higher than the Si_3N_4 one, the absolute maximum is on the plane where the thickness of the Si_3N_4 is equal to zero. If we fix, respectively, the Si and Si_3N_4 thicknesses at 100 and 50 nm, the maximum curvature is reached for an Al thickness of approximately 50 nm. Of course, due to other requirements concerning the electrical conductivity and isolation issues, it is not always possible to make a trilayered microstructure with thicknesses that completely maximize the curvature. However, the above analysis shows us that to increase the deflection we have to maximize the moment that generate the bending. That is why for a maximum curvature the two materials that will contract more have to be put in the geometrical upper part of the trilayers.

Another possibility of modifying the deflection of the microstructure is to change the deposition temperature of Al. In Fig. 8, we can see how the curvature is modified as a function of that parameter. The curvature becomes negative and the structure bends downwards if Al is deposited at a temperature lower than 200°C. It explains why the trilayered cantilever bends down to the substrate surface (Fig. 3c) before the thermal treatment (Fig. 3d).

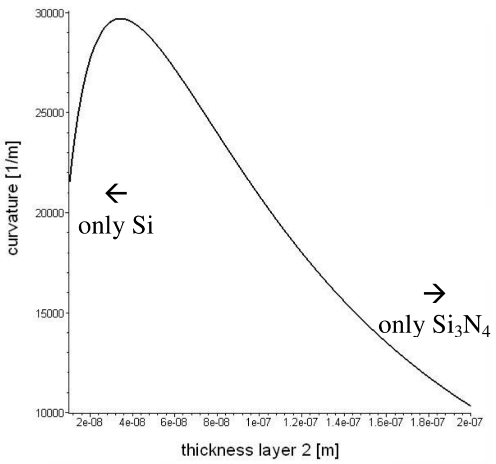

Figure 6: Bilayered cantilever curvature as a function of the Si_3N_4 layer thickness.

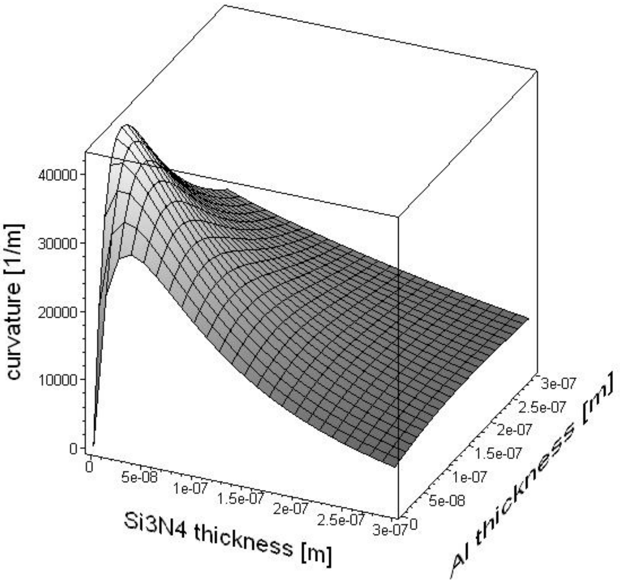

Figure 7: Trilayered cantilever curvature as a function of Si_3N_4 and Al thicknesses.

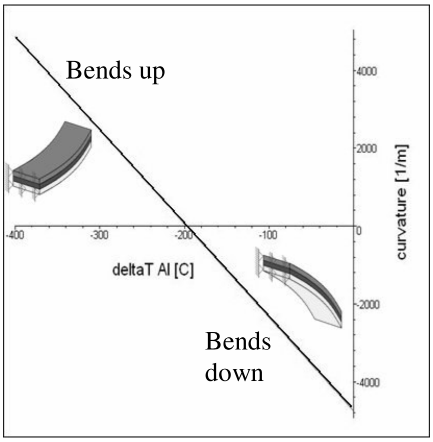

Figure 8: Trilayered cantilever curvature as a function of the Al layer deposition temperature.

6 - CONCLUSIONS

We have presented the fabrication process for obtaining 3-D MEMS in thin SOI technology. This process is compatible with the fabrication of MOS integrated circuits with very good performance in harsh conditions. Thus, this kind of MEMS can be directly integrated with electronic components and space applications are one of the most promising fields of application.

The 3-D shape of theses MEMS is obtained through the control of the thermal stresses during fabrication. Taking into account the materials employed, the stress control is made by an adequate design of the geometry and through the application of additional thermal treatments if it is necessary.

We have also shown how the fabrication of these MEMS can be simulated numerically with a finite element code. Given the characteristics of these MEMS, a geometrical nonlinear analysis with a strong coupling between mechanical and thermal fields has to be taken into account for obtaining realistic results. Besides the access to information that most of the time is difficult to obtain experimentally (e.g. intermediate stresses), simulations are an important tool in the design process because allow the optimization of the system without making too many physical prototypes.

Although the focus of this work was mainly on the fabrication phase, the multiphysics characteristic of the Oofelie code makes the simulation of the operation stage totally feasible. During operation, not only the coupling between mechanical and thermal fields is needed, but also the electrical part has to be included as well as new materials with, for example, piezoelectric behavior. The modeling of the operation of the flow sensor and the thermal actuator of Fig. 1 will be the next steps in our simulations.

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